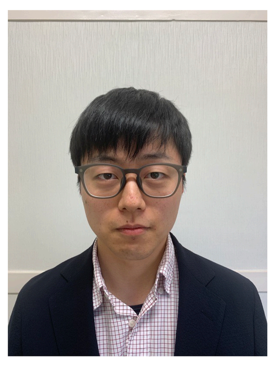
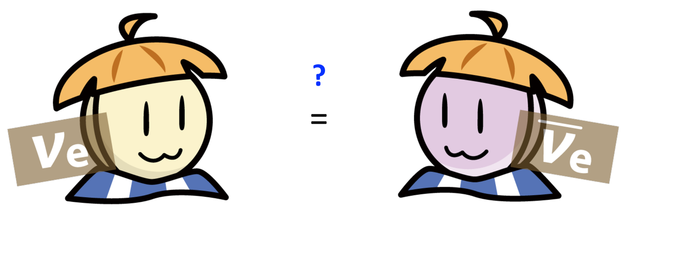
Progress and future of neutrino-less double-beta decay search by the KamLAND-Zen experiment



65

RCNS, Tohoku University
Nanami Kawada
kawada@awa.tohoku.ac.jp

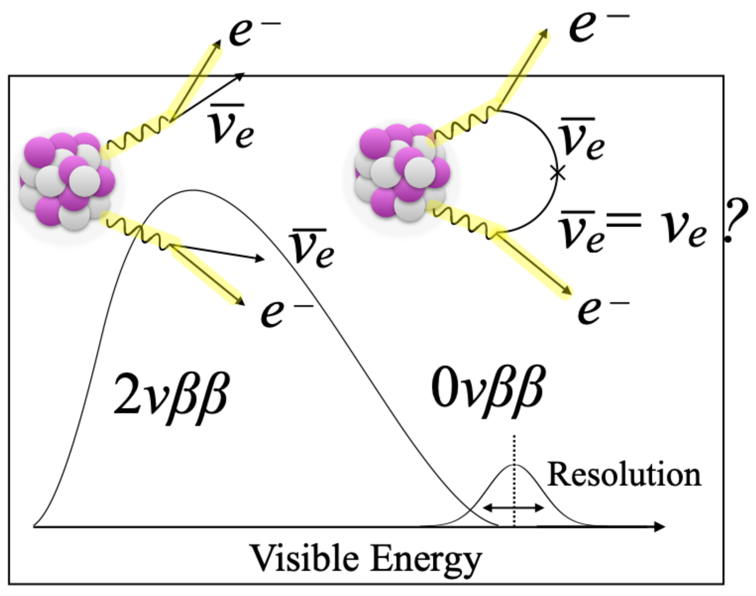
Neutrino-less double-beta decay



https://higgstan.com/

Majorana neutrino

- Neutrino can be Majorana particle.
- Majorana neutrino is key componet of
  - Tiny neutrino mass (via SeeSaw mechanism)
  - Matter dominant universe (via Leptogenesis)



Neutrino-less double-beta decay (0νββ)

- It happens only if ν is Majorana particle.

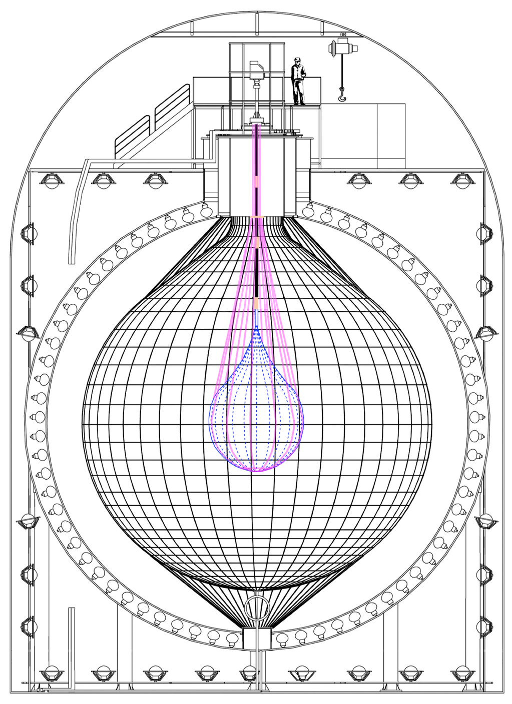
Proof of Majorana neutrino

- Experiment: peak search around the Q-value
- Requirements: large exposure, background reduction

KamLAND is a suitable detector

KamLAND-Zen experiment

Zero-**n**eutrino double-beta decay search with **KamLAND** detector



KamLAND-Zen

Advantage of using the KamLAND detector

- Ultra-low radioactive environment – U, Th ≤ 10^{-17} g/g
- Huge & scalable – 1kt liquid scintillator

→ Ideal environmet for extremely rare decay search !!

Double-beta decay source : ^{136}Xe

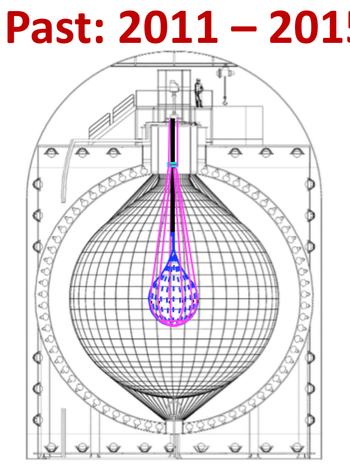
- 0νββ Q-value : 2.46 MeV (below ^{208}Tl γ BG)
- Long 2νββ half life (fewer 2νββ BG)
- **(Relatively)** easy to enrich/purify by distillation (^{136}Xe is enriched to ~90%)
- Dissolved into liquid scintillator (LS) at 3% (stable in room temperature and pressure)

Mini-balloon installed to support xenon-loaded LS (XeLS)

- Outer LS provides passive shielding from external radioactive background.
- Concentrated target nuclei can suppress volume-proportional backgrounds.

History and future of KamLAND-Zen

Past: 2011 – 2015

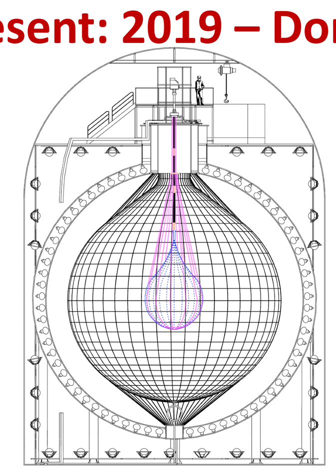


KamLAND-Zen 400

- Mini-balloon radius = 1.54 m
- 320–380 kg of enriched xenon
- $\langle m_{\beta\beta}\rangle < 61\text{–}165$ meV

Phys. Rev. Lett. 117, 082503 (2016)

Present: 2019 – Done!!



KamLAND-Zen 800

- Mini-balloon radius = 1.90 m
- 745±3 kg of enriched xenon

Phys. Rev. Lett. 130, 051801 (2023)

Cleaner mini-ballon, more xenon for better sensitivity

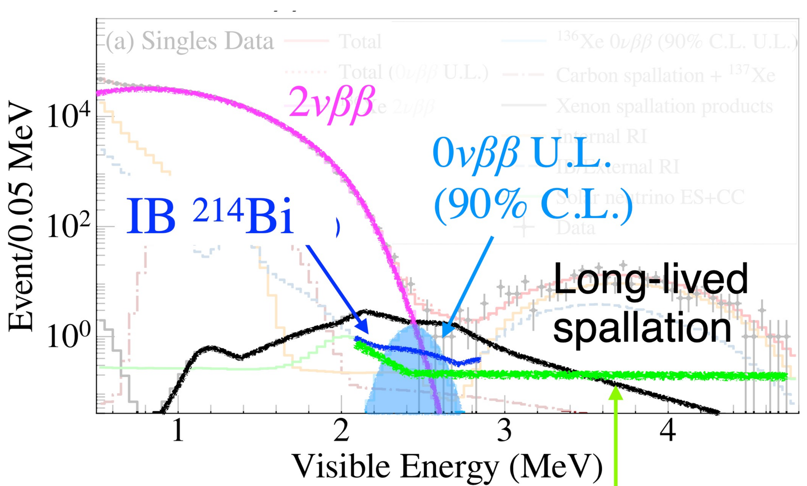
Near future

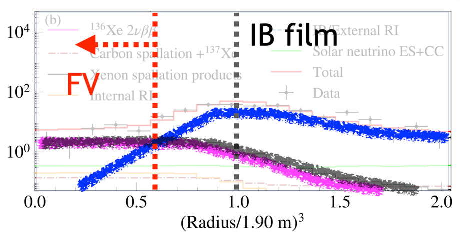
KamLAND2-Zen

- Detector upgrade for better energy resolution
- ~1 ton of enriched xenon

Toward $\langle m_{\beta\beta}\rangle = 20$ meV !!

Backgrounds of 0νββ signal





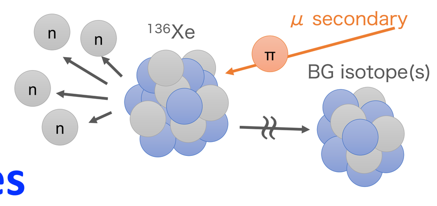
Electron scattering + ^{136}Xe CC by solar neutrinos

Double-beta decay of ^{136}Xe ($2\nu\beta\beta$)

Long-lived spallation products

Generated in μ spallation on ^{136}Xe
Tagged with μ-n's-spallation triple coincidence

- 42±8.8% rejection with 8.6% signal sacrifice
- Still major background

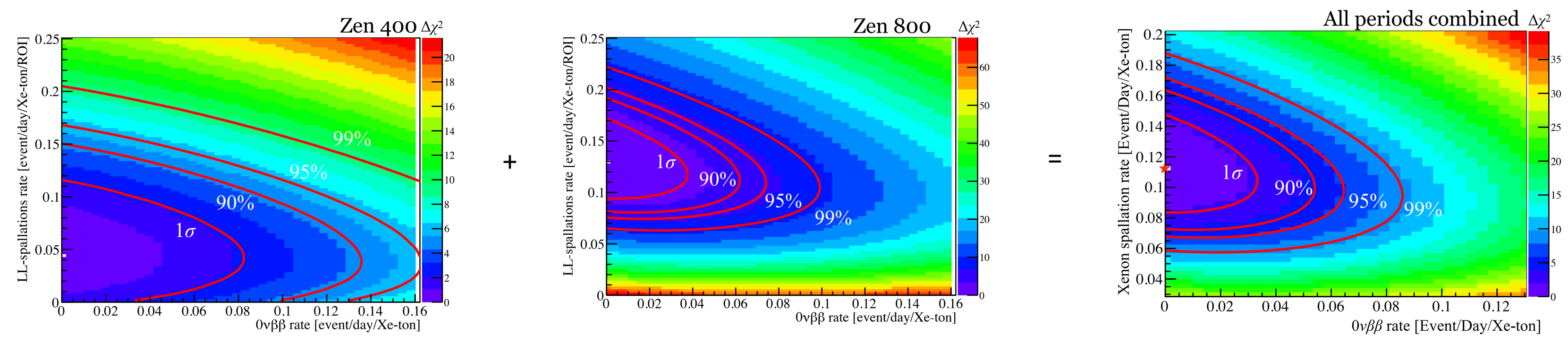


Radioactive impurities

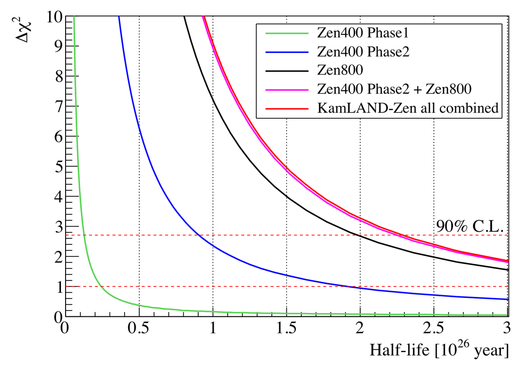
Solar neutrinos

Result from KamLAND-Zen 800 (Phys.Rev. Lett. 130, 051801)

Δχ² map of 0νββ rate and L.L. rate in ROI

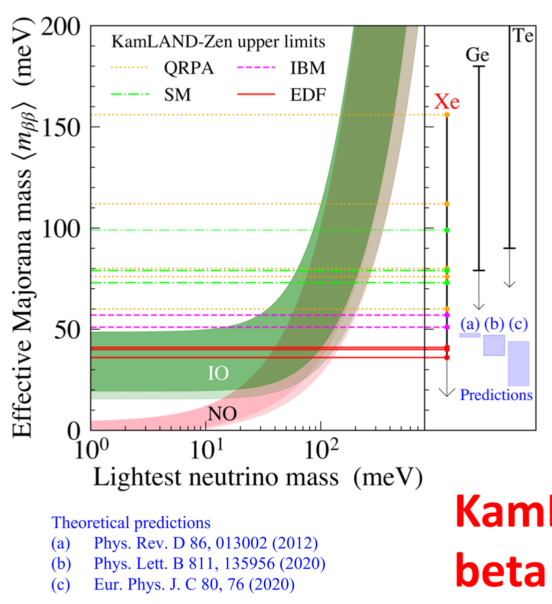


Δχ² profile of 0νββ-half life



- KamLAND-Zen 400 dataset was re-analyzed with the new strategy.
- Zen400 and Zen800 datasets were combined in Δχ² map.
- 0νββ half-life lower limit (90% C.L.):
  - Zen400 : 0.9 × 10^{26} years
  - Zen800 : 2.0 × 10^{26} years
  - Combined : **2.3 × 10^{26} years → 2x better half-life limit !!**
- This analysis gave **the most precise measurement of Xe spallation.**

Limit on ν mass



Theoretical predictions
(a) Phys. Rev. D 86, 013002 (2012)
(b) Phys. Lett. B 811, 135956 (2020)
(c) Eur. Phys. J. C 80, 76 (2020)

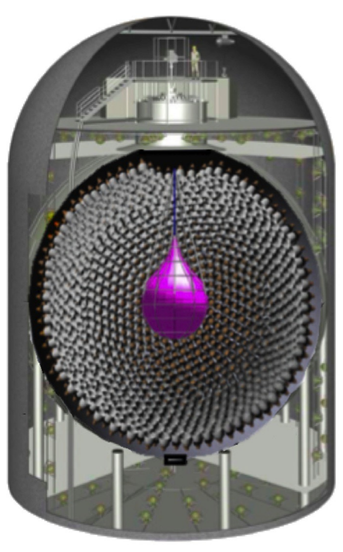
- Combined $(T^{0\nu}_{1/2})^{-1}$ lower limit (**2.3 × 10^{26} years**) is translated to

$$\langle m_{\beta\beta}\rangle < 36 - 156 \text{ meV}$$ with different NMEs.

Phys. Rev. Lett. 130, 051801 (2023)

KamLAND-Zen achieved the first search for neutrinoless double-beta decay in the inverted mass ordering region below 50 meV.

Toward further sensitivity

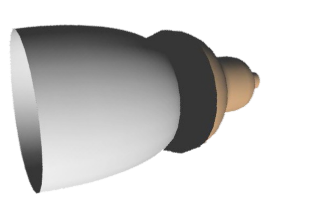


KamLAND2-Zen

What we can do for 2νββ background reduction?

- Separation by observed energy is the only way.
- **Energy resolution is definitive.**

Detector upgrade plan



- Light yield increase by
  - High light-yield scintillator (x1.4)
  - Light-correcting Winston cone on PMTs (x1.8)
  - High quantum efficiency PMT (x1.9)

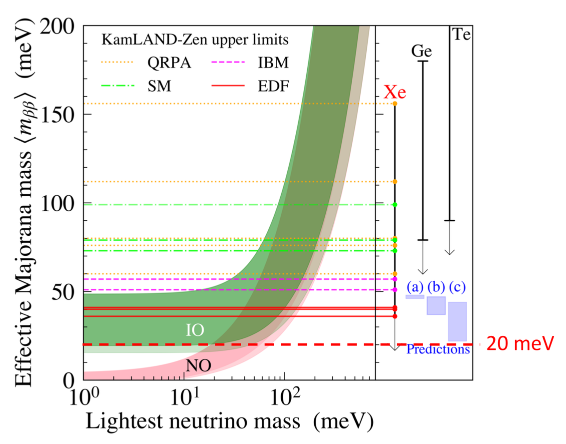
  ✓5x increased effective light yield
  ✓Twice better energy resolution@Q-value
  ✓2νββ background reduction by order of 2.

- State-of-the-art read-out electronics: MoGURA2
  - RFSoC powered data acquisition
  - Huge buffer for SN-burst detection

  ✓~100% spallation neutron detection
  ✓More efficient L.L. tagging

- Increased xenon: 745 kg → 1,000 kg

  ✓More xenon, more exposure.



Target sensitivity

- The half-life : 2.0 × 10^{27} year
- $\langle m_{\beta\beta}\rangle \sim 20$ meV (in 10 years)

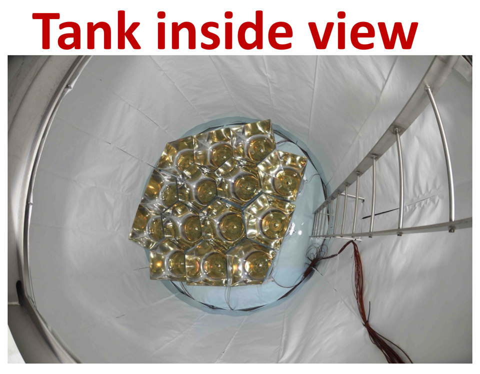
KamLAND2-Zen will be the first search to cover the inverted mass ordering region !!

KamLAND2 prototype

Tank overview

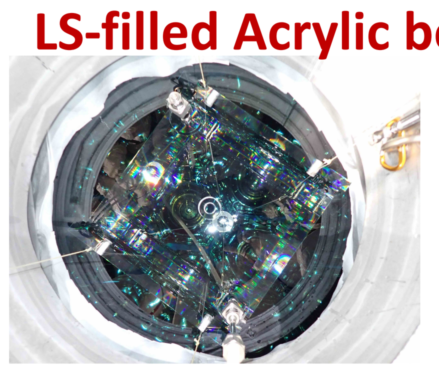
50 m³ tank was built for benchmark of light-yield increase.

Tank inside view



14 PMTs were installed with Winston cones. The tank is filled with filtered water.

LS-filled Acrylic box

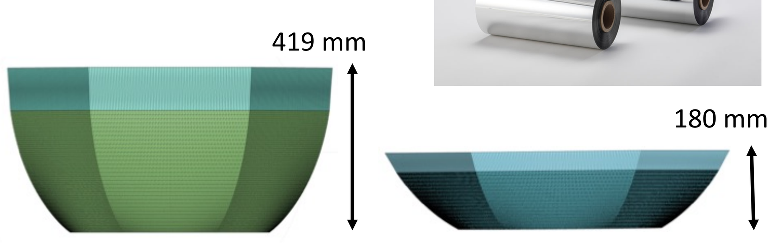


LAB LS is filled into 30 cm x 30 cm x 30 cm acrylic box and installed at the center.

The ~x2 increase in light yield by light collection mirror was demonstrated.

Feedback to mirror structure

- The height has been changed for ease in installation.
- Mirror top edge was replaced with sheet mirror to avoid deformation due to mirror-to-mirror contact.



Summary

- The KamLAND-Zen experiment has been the forefront of the 0νββ search for more than a decade.
- The upcoming phase of KamLAND-Zen, KamLAND2-Zen, will implement a lot of new technologies to increase sensitivity and aim to start in 2027 !!